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# PREDICTED PERFORMANCE OF A 15-80 $kW_e$ REACTOR BRAYTON POWER SYSTEM OVER A RANGE OF OPERATING CONDITIONS

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ABSTRACT

A computer simulation of a 15-80 $kW_e$ nuclear reactor Brayton cycle power system designed for a turbine inlet temperature of 1150° F was used to study the steady-state performance of the system at turbine inlet temperatures between 1050 and 1600° F. The low end of the temperature range is of interest in applications using a zirconium hydride reactor heat source, while the 1600° F temperature assumes the use of an advanced reactor. Cycle-parameter effects and predicted system efficiency and required radiator area are presented over a range of compressor inlet temperatures and turbine inlet temperatures. The performance over a range of power levels is also presented.

E-6309

A 15 TO 80 $kW_e$ REACTOR-POWERED Brayton-cycle power conversion system is described in (1)* along with its predicted design-point performance. The ability of a closed Brayton cycle power system to operate with good performance over a range of power levels and cycle conditions permits a single developed system to be used for a variety of applications or missions. These missions may have different power requirements or may require selection of different cycle operating conditions in order to meet available surface limitations on radiator area. Also, by operating at reduced power or reduced turbine inlet temperature during extended periods of low power requirements, reactor life may be extended. The 15-80 $kW_e$ system of (1) incorporates the capability of operating at turbine inlet temperatures up to 1600° F. The capability of operating over a range of turbine inlet temperatures permits the same conversion system to accommodate future increases in reactor outlet temperature.

Because of such possible range of applications, it is of interest to examine the performance and radiator requirements of the conversion system described in (1) over a range of power level, compressor inlet temperature, and turbine inlet temperature. It is the purpose of this paper to present the results of such a study.

SYSTEM DESCRIPTION

A schematic diagram of the system is shown in Fig. 1. It includes a primary NaK loop; the Brayton cycle gas loop; and two organic-coolant heat-rejection loops, one for the cycle waste heat and the other for component cooling. For operation at a turbine inlet temperature of 1600° F, lithium is used in the primary loop as the coolant for an advanced reactor. The cycle working fluid is a helium-xenon mixture of 40 molecular weight.

METHOD

It was assumed in this study that all components of the gas loop - that is, the Brayton conversion system loop - are fixed. This includes the gas ducting, heat exchangers, and the turbomachinery. Radiator area was

*Numbers in parentheses designate References at end of paper.

sized to meet the particular cycle requirements. An equivalent sink temperature of +10° F and emissivity of 0.88 were assumed for turbine inlet temperatures between 1050 and 1250° F. A different radiator coating was assumed to be required at a turbine inlet temperature of 1600° F, with assumed properties resulting in an equivalent sink temperature of +40° F and an emissivity of 0.90. Liquid loop components in the primary, intermediate, and heat rejection loops were assumed to be sized to maintain constant pressure drops. The digital computer program, with modifications, and the techniques developed in (2) were used in this study.

The effects of variations in power level, compressor inlet temperature, and turbine inlet temperature on system performance were investigated. Changes in power level are effected in the system through changes in the working-gas inventory of the Brayton cycle gas loop, appearing as changes in loop operating pressure.

COMPONENT PERFORMANCE MODELS - Performance maps for the compressor and turbine were obtained by scaling from similar equipment previously tested at NASA (Lewis) and were normalized to the estimated design-point performance. The compressor design-point efficiency was 0.83 at a pressure ratio of 1.80. The turbine design-point efficiency was 0.90 at a pressure ratio of 1.73. Alternator electromagnetic efficiency was computed from an existing NASA (Lewis) computer program (3); a plot of electromagnetic efficiency as a function of power level is shown in Fig. 2.

Heat transfer and gas pressure drop models were similar to those of (2) in which variations about design point values were calculated as a function of the related variables. Design point values of heat exchanger effectiveness are shown in Fig. 1.

PARASITIC LOSSES - The following parasitic losses were included in the study:

1. A fixed thermal loss of 3kW was assumed to occur through the insulation of the conversion system.

2. A total of 2 percent of the compressor discharge flow was assumed to be bled off for pressurizing the gas-bearing cavities. The effect of this bleed flow on cycle performance was estimated by consideration of the leakage paths and effect upon temperature resulting from mixing of the gas streams.

3. Bearing losses were estimated to be 2.5 kW based on the studies of (4) and (5). They were assumed to be constant over the operating range.

4. Alternator windage loss was calculated for a cavity pressure equal to compressor inlet pressure and a cavity temperature of 220° F. Drag coefficients for the alternator surfaces were obtained from the studies reported in (6).

5. Pumping power requirements were calculated assuming fixed loop pressure drops of 7 psi, 5 psi, and 35 psi in the primary loop, intermediate loop, and each heat rejection loop, respectively. Primary and intermediate loop pumps were assumed to be AC induction EM pumps, and motor-driven centrifugal pumps were assumed in the heat rejection loops.

6. Control power was assumed to consist of a fixed 500 watts, plus a variable amount equal to 3 percent of the alternator gross output.

## RESULTS

The results of the study show the effects of variations in power level, compressor inlet temperature, and turbine inlet temperature on cycle operating parameters as well as on system performance. Each set of values represents an operating point on the compressor and turbine maps which satisfies the loop pressure drop requirements. Figure 3 is a plot of the compressor map showing the operating regions covered in the study. It is a conventional plot of compressor pressure ratio as a function of corrected mass flow. Curves of corrected speed from 70 percent to 120 percent of design speed are shown, with contours of constant compressor adiabatic efficiency. The two shaded operating regions represent operation at turbine inlet temperatures of 1150° F and 1600° F. The circled point is the design point. Changes in power level at constant compressor and turbine inlet temperature are represented by movement across the width of each operating region, at a constant corrected speed. It is seen that little change in compressor ratio or efficiency results from changes in power level. This is also true of the turbine. Reynolds numbers for both compressor and turbine are sufficiently high that their influence on efficiency is minor. Changes in compressor inlet temperature result in movement along the length of each operating region. Increases in compressor inlet temperature result in reduced corrected speed, corrected mass flow, and pressure ratio. Higher turbine inlet temperatures shift the operating region to lower values of pressure ratio and corrected mass flow, with little change in efficiency.

EFFECT OF POWER LEVEL - The effect of net power level on several cycle parameters is shown in Fig. 4 for the design turbine inlet temperature of 1150° F and cycle temperature ratio of 0.38 (compressor inlet/turbine inlet). System net power is the power available after subtracting pumping and control power requirements. The net power range from 15 to 80 $kW_e$ corresponds to a range of alternator gross output power from 21 to 93 kW. The increase in compressor inlet pressure with increase in power reflects the increase in gas inventory and mass flow rate required for higher power operation. The compressor pressure ratio changes very little with power level as noted previously. There are, however, significant changes in loss pressure ratio, L, and recuperator effectiveness, E, as net power is increased from 15 to 80 $kW_e$. Loss pressure ratio, L, is defined as the ratio of the turbine pressure ratio to compressor pressure ratio and is a function of the pressure drop in the gas loop. The gas loop relative pressure loss, $\Delta p/p$, is approximately equal to the difference between 1.0 and L. The value of L increases from 0.935 at 15 $kW_e$ to 0.965 at 80 $kW_e$, corresponding to a decrease in relative pressure drop, $\Delta p/p$, from 6.5 percent to 3.5 percent. This decrease in pressure drop is due primarily to a decrease in friction factor with increasing Reynolds numbers at the higher powers. The recuperator effectiveness, E, decreases from 0.964 to 0.910 as a result of the increased thermal load with increased power level. The changes in L and E tend to offset each other so that there is only a small change in cycle efficiency over the power range.

The variation in specific radiator area, ($ft^2/kW_e$), and conversion system efficiency with net power is shown in Fig. 5. The radiator area is the total area for both cycle waste heat and component cooling requirements. Conversion system efficiency is defined as the ratio of net electric power to thermal power into the heat source heat exchanger. A peak efficiency of 19.5 percent with a specific radiator area of 65 $ft^2/kW_e$ is obtained near the design net power of 60 $kW_e$. At 15 $kW_e$, the efficiency is about 15 percent and the specific radiator area is 85 $ft^2/kW_e$. There is only a small change in efficiency and specific radiator area between 60 and 80 $kW_e$.

EFFECT OF CYCLE TEMPERATURE RATIO - The effect of cycle temperature ratio upon the cycle parameters is shown in Fig. 6 for a turbine inlet temperature of 1150° F and a net power of 60 $kW_e$. For a constant turbine inlet temperature, an increase in cycle temperature ratio represents an increase in compressor inlet temperature. This results in a decrease in compressor pressure ratio because of the approximately fixed specific work capability (Btu/lb) of the compressor operating at a constant rotational speed. Compressor pressure ratio decreases from 1.99 at a cycle temperature ratio of 0.32 to 1.70 at a cycle temperature ratio of 0.42. The increase in compressor inlet pressure with cycle temperature ratio is a result of increased mass flow required to maintain a fixed power output at the lower efficiency cycle operating conditions. This increase in pressure results in a decrease in system pressure drop as indicated by the increasing value of L, and a decrease in recuperator effectiveness, E. These effects are similar to those occurring with increase in power level.

The effect of cycle temperature ratio on the overall system characteristics is shown in Fig. 7 for a turbine inlet temperature of 1150° F. Total specific radiator area is plotted against conversion system efficiency. Curves for three power levels are presented and lines of constant cycle temperature ratio are shown. The 15 $kW_e$ and 80 $kW_e$ curves represent operation near the extremes of the system power range, while the 60 $kW_e$ curve represents operation at the design power level. These curves are useful in showing the tradeoff that can be made between radiator area and efficiency for a fixed conversion system. Thus, varying mission requirements as to allowable radiator area and reactor power can be accommodated through adjustment in the compressor inlet temperature or cycle temperature ratio. For example, conversion system efficiencies from about 16 percent to 23 percent are obtainable at specific radiator areas ranging from 58 to 82 $ft^2/kW_e$ at a net power level of 60 $kW_e$.

EFFECT OF TURBINE INLET TEMPERATURE - The effect of turbine inlet temperature on the cycle parameters is shown in Fig. 8. Curves of compressor inlet pressure, compressor pressure ratio, system loss pressure ratio, and recuperator effectiveness are plotted as a function of cycle temperature ratio for turbine inlet temperatures of 1600° F and 1150° F at a net power of 60 $kW_e$. Compressor inlet pressure increases between 5 and 10 psi as the turbine inlet temperature increases from 1150° F to 1600° F at the same cycle temperature ratio. Compressor pressure ratio decreases with increase in turbine inlet temperature at the same cycle temperature ratio because of the higher compressor inlet temperature. Values of both system loss pressure ratio, L, and recuperator effectiveness, E, increase at the higher turbine inlet temperature.

The effect of turbine inlet temperature on the system characteristics is presented in Fig. 9. Specific radiator area is plotted against conversion system efficiency for a range of turbine inlet temperatures from 1050 to 1600° F at a net power of 60 $kW_e$. The three lowest temperatures assume the use of a ZrH reactor at a design reactor outlet temperature of 1200° F and at temperatures 100° F above and below this value. The curve for 1600° F assumes the use of an advanced, lithium-cooled reactor.

Specific radiator area changes rapidly with turbine inlet temperature in the temperature range of the ZrH reactor. A 100° F decrease in turbine inlet temperature from the design value of 1150° F results in approximately a 45 percent increase in specific radiator area at the same cycle temperature ratio. An increase of 100° F results in a decrease in radiator area of about 25 percent. An increase of approximately 0.01 in conversion system efficiency also occurs with increase in turbine inlet temperature from 1050° F to 1250° F. At a turbine inlet temperature of 1600° F and a cycle temperature ratio of 0.38, the specific radiator area is reduced to about 24 $ft^2/kW_e$ from the 65 $ft^2/kW_e$ required at 1150° F. Conversion system efficiency increases by approximately 0.02. Specific radiator area of less than 30 $ft^2/kW_e$ can be achieved at efficiencies up to about 28 percent.

## SUMMARY OF RESULTS

A study was made of a reactor power system using a fixed Brayton conversion module to predict performance characteristics over a range of power level, cycle temperature ratio, and turbine inlet temperature. The system was designed at 60 $kW_e$ of net power at a turbine inlet temperature of 1150° F and a cycle temperature ratio of 0.38. The principal results were as follows:

1. Operation over a net power range from 15 to 80 $kW_e$ at design cycle temperatures resulted in net system efficiencies of 15 to 19.5 percent and specific radiator areas from 86 to 65 $ft^2/kW_e$, respectively.
2. Operation over a range of cycle temperature ratios at design turbine inlet temperature and design power permits a tradeoff between system efficiency and specific radiator area. A specific radiator area of 58 $ft^2/kW_e$ was achievable at a system efficiency of 0.15, while a system efficiency of 0.23 could be obtained at a specific radiator area of 82 $ft^2/kW_e$.
3. Operation over a range of turbine inlet temperatures resulted in large changes in specific radiator area requirements. In the temperature range suitable for ZrH reactor and at design cycle temperature ratio and power, specific radiator area requirements decreased from 92 $ft^2/kW_e$ at 1050° F to 58 $ft^2/kW_e$ at 1250° F. Corresponding system efficiencies were between approximately 19 and 20 percent. Increasing the turbine inlet temperature to 1600° F through the use of an advanced reactor resulted in specific radiator areas less than 30 $ft^2/kW_e$ at system efficiencies up to about 28 percent.

## REFERENCES

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2. J. L. Klann, "Steady-State Analysis of a Brayton Space Power System." NASA TN D-5763, 1970.

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5. R. A. Rackley, ed., "Nuclear Brayton Turboalternator-Compressor (TAC) Conceputal Design Study." AiResearch Mfg. Co. Report APS-5355-R, Sept. 1970.

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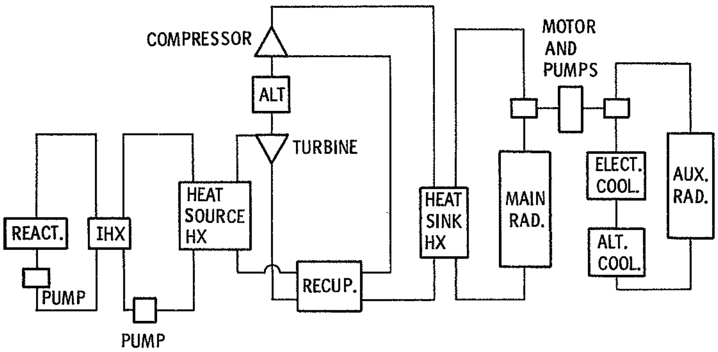
E-6309




DESIGN CONDITIONS

| | |
|---|---|
| TURBINE INLET TEMPERATURE | $1150^{\circ}$ F |
| CYCLE TEMPERATURE RATIO | 0.38 |
| COMPRESSOR PRESSURE RATIO | 1.80 |
| LOSS PRESSURE RATIO, L | 0.96 |
| RECUPERATOR EFFECTIVENESS, E | 0.925 |
| COMPRESSOR INLET PRESSURE, PSIA | 70 |
| HEAT SINK HX EFFECTIVENESS | 0.95 |
| NET POWER, kWe | 60 |

Figure 1. - Reactor Brayton system schematic.

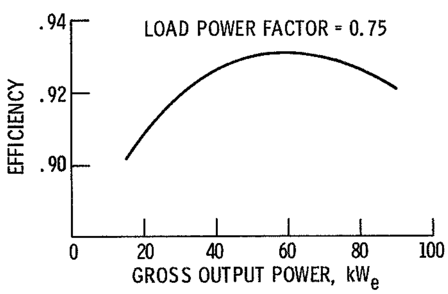



Figure 2. - Alternator electromagnetic efficiency.

E-6309

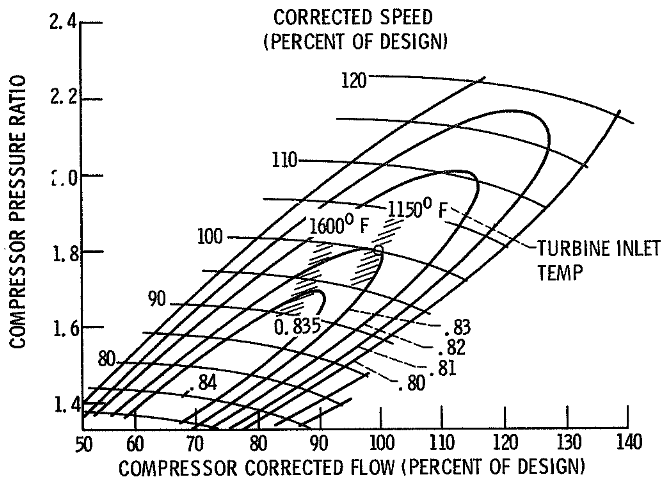



Figure 3. - Compressor performance map with system operating regions.

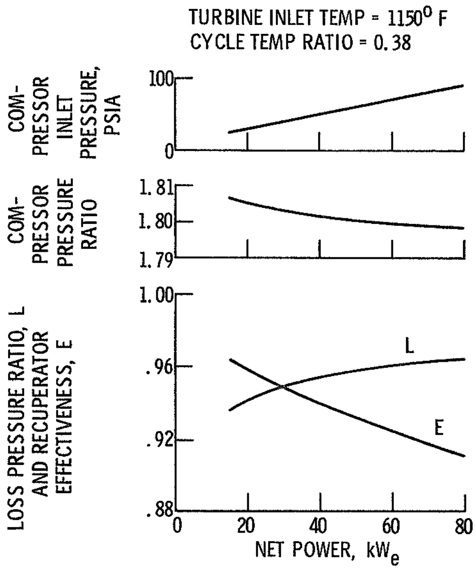



Figure 4. - Effect of power level on cycle parameters.

E-6309

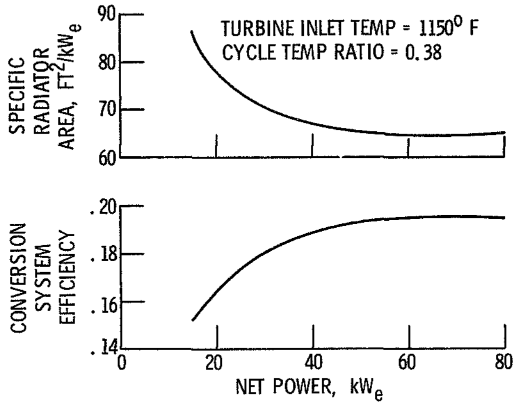



Figure 5. - Effect of power level on radiator area and efficiency.

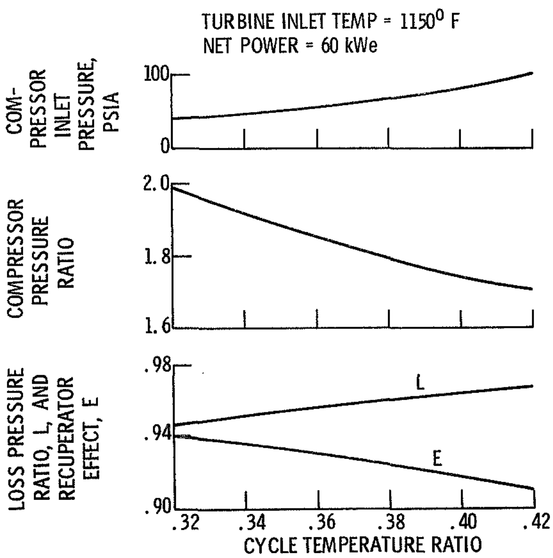



Figure 6. - Effect of cycle temperature ratio on cycle parameters.

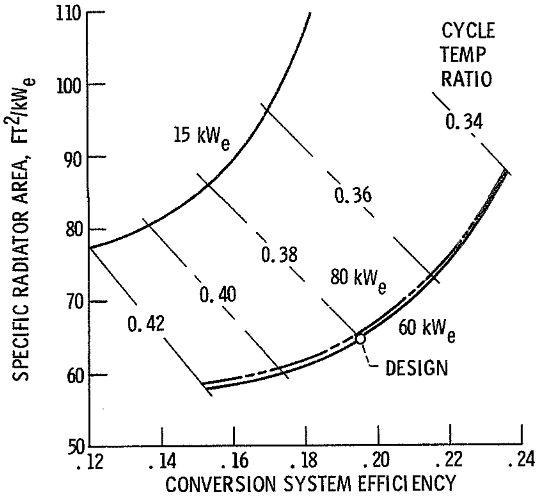



Figure 7. - System performance characteristics at a turbine inlet temperature of 1150° F.

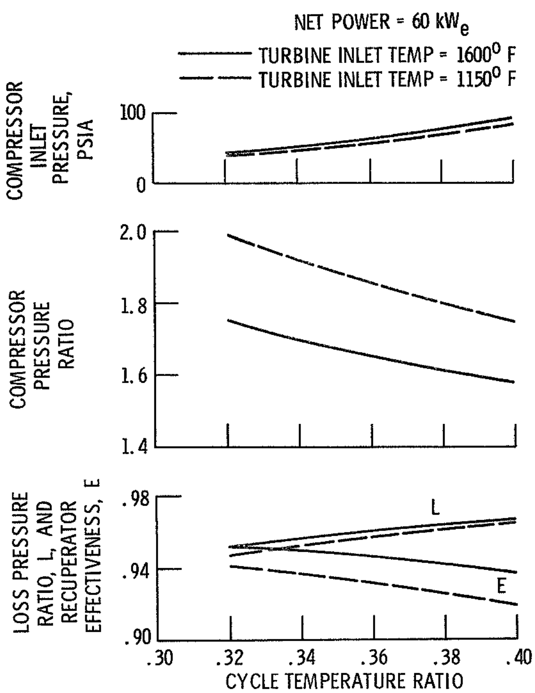



Figure 8. - Effect of turbine inlet temperature on cycle parameters.

E-6309

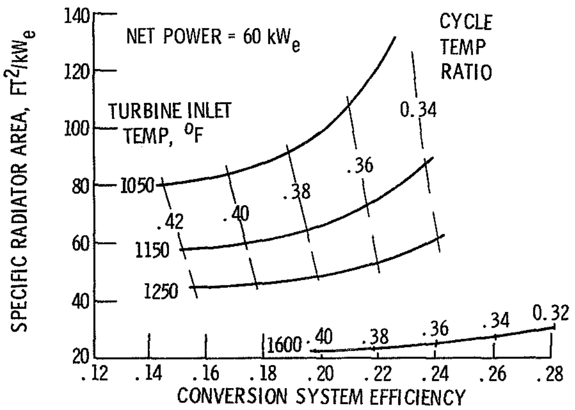



Figure 9. - Effect of turbine inlet temperature on system performance characteristics.